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NUMERICAL MODELLING OF METHANE GAS MIGRATION IN DRY COAL SEAMS

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SUMMARY

This paper presents the development of a mathematical model for methane gas migration in coal seams. The major focus of this model is the coupling between the gas flow and deformation of solid coal. The effect of diffusion of adsorbed methane gas from the solid matrix to the voids has been taken into account. The adsorption of gas in the coal seam causes a two-phase state of gas flow. The governing equation for the two-phase gas flow is a non-linear partial differential equation with non-linear boundary conditions. A finite element model has been developed for simulation of the distribution of pressure and concentration of methane gas due to gas migration in coal seams.

KEY WORDS: methane gas; finite element; coal mining; diffusion; adsorption; outbursts

1. INTRODUCTION

The emission of methane gas in coal mines is very important for safety as well as for economic reasons since it is a source of natural gas production. The mechanism of methane gas migration in coal seams is based on the coupling of flow and deformation in porous media. The problem of coupled fluid flow and deformation in porous media has been investigated in the past.[1,2] The investigation of fluid flow in porous fractured media[3,4] and mass transfer problems in porous fractured media[5,6] has also been carried out. However, the problem of coupled mass transfer, multi-phase gas flow and medium deformation in porous media subjected to stress changes has not been solved so far.

The porosity of geological materials such as coal seams is influenced by the magnitude of the confining pressure. The porosity characteristics may vary drastically due to stress relaxation associated with excavation. Since both dispersivity and permeability of a porous fractured medium are basically functions of porosity and tortuosity of the interconnected network of void spaces, they also depend on *in situ* stresses. Therefore, the problem of mass transfer and multi-phase gas flow in porous fractured media may cause a strong non-linearity in the coupling of gas pressure, mass concentration and stress deformation.

The release of methane gas from coal seams into mine workings is of great concern due to the occurrence of a number of serious hazards such as gas outburst in coal mines and the resulting loss of life. The advent of modern underground mining machinery and mining methods, coupled with improved environmental control techniques, has allowed higher levels of production to be achieved with faster rates of face advance. These factors, combined with increasing depth of workings, have increased the problems related to emission of methane gas in coal seams in

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underground mining. The presence of methane in coal seams represents a significant safety hazard due to gas outbursts caused by high-pressure gradients of methane gas in coal seams.

The gas outbursts in an underground coal mine occur as a violent spontaneous ejection of fragmentated coal/rock material and gas from the coal seam into the airways in working spaces. Usually, the gas outbursts are caused by overstressing in the coal seam. This is, predominantly, due to the influence of geological structures, *in situ* stress field, stress concentrations, high-pressure gradients and large volumes of gas desorbed in the coal seam. Consequently, the gas outbursts in coal mining can be considered to depend on the process of gas migration in the coal seam.

A number of studies indicate that an outburst can eject considerable amounts of coal ranging in magnitude from a few tonnes to several thousand tonnes, and gas from a few cubic metres to several thousand cubic metres.[7] The gases emitted can be methane or carbon dioxide or a mixture of both. The coal dust and gas ejected during an outburst may under certain conditions lead to a gas explosion. This may result in addition to an increase the airborne contamination of the mine environment subsequent destruction of mine structures, loss of mine equipment, and possible injury or death to miners. Thus, the analysis of gas migration in coal seams during gas outbursts is important to predict such outbursts in coal mining.

This paper presents a mathematical modelling of methane gas migration in coal seams. The major concern of this study is based on the combination of free gas transfer in the porous media and diffusion of adsorbed methane gas from the matrix of coal to the voids in the coal seam. In order to solve the coupled problem of the gas pressure, mass transfer and deformation of the medium during the methane gas migration, a relationship between gas pressure and mass concentration has been developed. It can be found that the effects of adsorption introduce a strong non-linear behaviour for gas pressure and concentration during gas migration. The finite element model has been developed on the basis of a combined non-linear gas flow and linear solid deformation equation

2. POROSITY AND PERMEABILITY OF ANISOTROPIC MEDIUM

So far, most models of methane gas migration have assumed that porosity and permeability are same in all directions. In practice, however, the coal seam is often layered (Figure 1), where the layers of coal seam are sandwiched between the layers of rock mass. In order to express porosity and permeability in an anisotropic medium, the principal anisotropic co-ordinates (x_1, x_2, x_3) and the Cartesian co-ordinates (x, y, z) are introduced.

Consider an elemental volume, $\Delta V = \mathrm{d}x_1, \mathrm{d}x_2, \mathrm{d}x_3$. The volume of voids in the elemental volume can be expressed using the volumetric ratio (porosity), Φ, as $\Delta V^* = \Phi\,\Delta V = (\mathrm{d}s_1^*\ \mathrm{d}s_2^*\ \mathrm{d}s_3^*)^{1/2}$, (Figure 2). The anisotropic property of porous medium can be illustrated by introducing a set of principal values, ϕ_1, ϕ_2, ϕ_3. Using the area density concepts

$$\phi_1 = \frac{\mathrm{d}s_1^*}{\mathrm{d}x_2\,\mathrm{d}x_3} \quad \phi_2 = \frac{ds_2^*}{\mathrm{d}x_3\,\mathrm{d}x_1} \quad \phi_3 = \frac{ds_3^*}{\mathrm{d}x_1\,\mathrm{d}x_2} \tag{1}$$

where $\mathrm{d}s_i^*$ is the area of pores in the principal directions. ϕ_i is called the *area reduction along x_i direction due to porosity*. The volume of voids and the volume of solids (the volume of net coal) in the elemental volume can be represented as $\Delta V^* = (\mathrm{d}s_1^*\ \mathrm{d}s_2^*\ \mathrm{d}s_3^*)^{1/2}$ and $\Delta V_s = (1 - \Phi)\,\Delta V$ respectively. Thus, we can find the relation between the porosity and the reduction rate of area is

$$\Phi = (\phi_1\ \phi_2\ \phi_3)^{1/2} \tag{2}$$

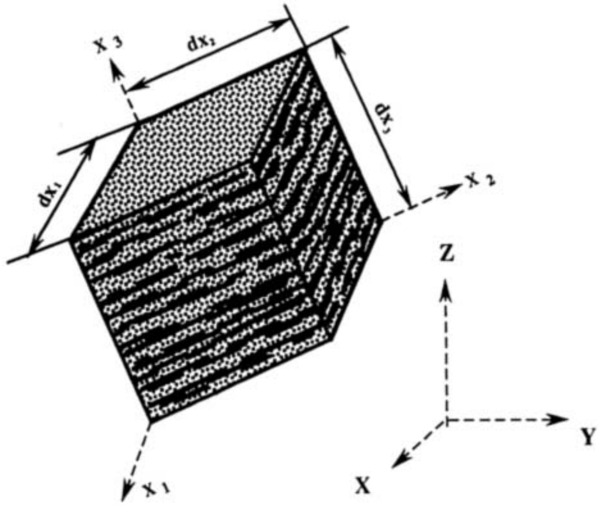
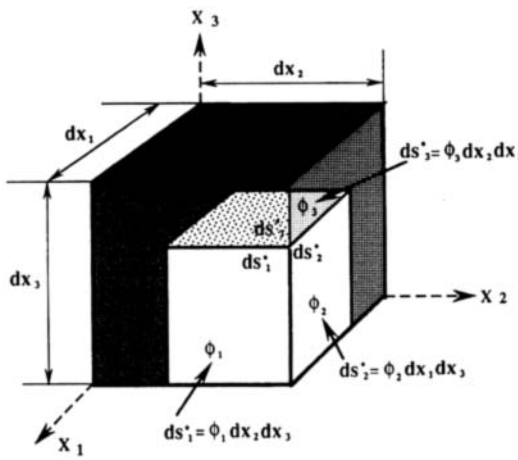


Figure 1. Orientation of layered coal seam



$$\Phi = \frac{\Delta v^*}{\Delta v} = \frac{(ds_1^* \, ds_2^* \, ds_3^*)^{\frac{1}{2}}}{dx_1 \, dx_2 \, dx_3} = (\phi_1 \phi_2 \phi_3)^{\frac{1}{2}}$$

Figure 2. Porosity representation for anisotropic medium

In order to simplify the solution of the problem, the methane gas flow can be approximately based on Darcy's law. Darcy's law for an anisotropic medium can be written in terms of (x_1, x_2, x_3) co-ordinate system. Denoting the components of the specific discharge vector of gas flow in x_i direction as

$$q_i = -\frac{k_i}{\mu}\frac{\partial P}{\partial x_i} \quad \text{(no summation for } i\text{)} \tag{3}$$

Table I

Direction	Flow in	Flow out
x_1	$\rho_g v_1 \phi_1 \, dx_2 \, dx_3$	$\rho_g v_1 \phi_1 \, dx_2 \, dx_3 + \frac{\partial}{\partial x_1}(\rho_g v_1 \phi_1 \, dx_2 \, dx_3) dx_1$
x_2	$\rho_g v_2 \phi_2 \, dx_3 \, dx_1$	$\rho_g v_2 \phi_2 \, dx_3 \, dx_1 + \frac{\partial}{\partial x_2}(\rho_g v_2 \phi_2 \, dx_3 \, dx_1) dx_2$
x_3	$\rho_g v_3 \phi_3 \, dx_1 \, dx_2$	$\rho_g v_3 \phi_3 \, dx_1 \, dx_2 + \frac{\partial}{\partial x_3}(\rho_g v_3 \phi_3 \, dx_1 \, dx_2) dx_3$

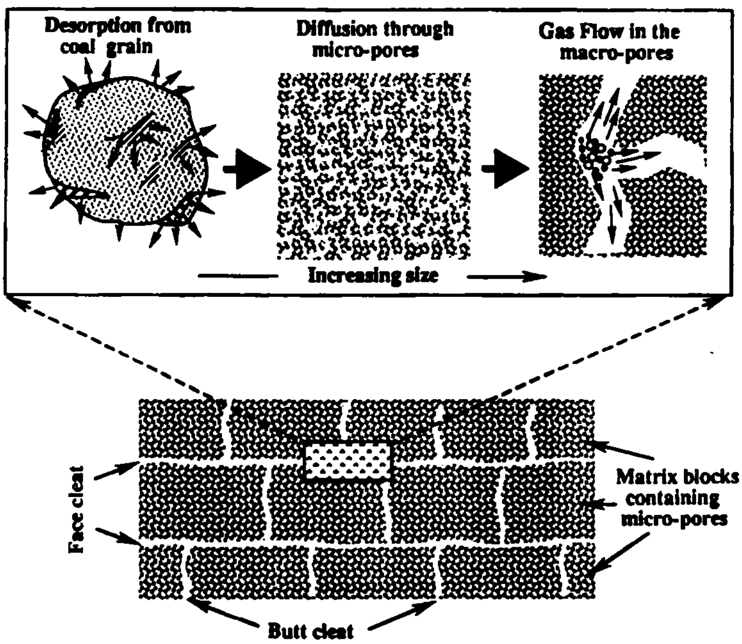


Figure 3. Migration process of methane gas in the coal matrix.[13]

where k_i represents the intrinsic permeability of coal along the direction x_i. k_1, k_2, k_3 are the principal values of anisotropic permeability, μ is the dynamic viscosity of the coal seam, and P is the gas pressure. It is possible to write Darcy's law in terms of the vector in (x, y, z) direction. In two-dimensional cases, we have

$$q_x = -\left(\frac{k_{xx}}{\mu}\frac{\partial P}{\partial x} + \frac{k_{xy}}{\mu}\frac{\partial P}{\partial y}\right) \tag{4a}$$

$$q_y = -\left(\frac{k_{yx}}{\mu}\frac{\partial P}{\partial x} + \frac{k_{yy}}{\mu}\frac{\partial P}{\partial y}\right) \tag{4b}$$

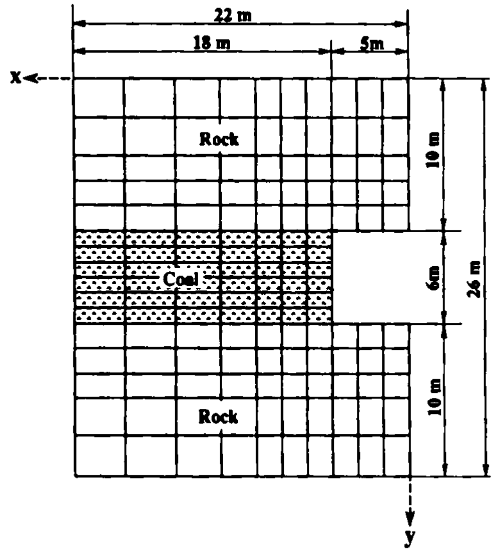


Figure 4. Finite element mesh for simulation of gas migration in coal seam

Table II. Material properties for solid medium[10-12]

Material property		Coal seam	Rock mass
Elastic modulus	E	$0{\cdot}741 \times 10^5$ (MPa)	$0{\cdot}245 \times 10^6$ (MPa)
Poisson's Ratio	ν	0·325	0·25
Porosity	Φ	0·083	Not used
Mass density	ρ_s	$0{\cdot}853 \times 10^{-3}$ (kg/cm^3)	$0{\cdot}255 \times 10^{-2}$ (kg/cm^3)
Permeability	k	$1{\cdot}00 \times 10^{-10}$ (cm^2)	Not used
Diffusibility of gas	G	$0{\cdot}46 \times 10^{-4}$ (cm^2/s)	Not used
Dynamic viscosity	μ	$0{\cdot}39 \times 10^{-8}$ (MPa s)	Not used

Note: The criteria adopted for finite element mesh division and time increment for Newmark Integration Scheme are given in Appendix III.

where

$$k_{xx} = -k_1 \cos^2 \alpha + k_2 \sin^2 \alpha \tag{5a}$$

$$k_{yy} = -k_1 \sin^2 \alpha + k_2 \cos^2 \alpha \tag{5b}$$

$$k_{xy} = k_{yx} = (k_1 - k_2) \cos \alpha \sin \alpha \tag{5c}$$

where α is the angle of anisotropic orientation.

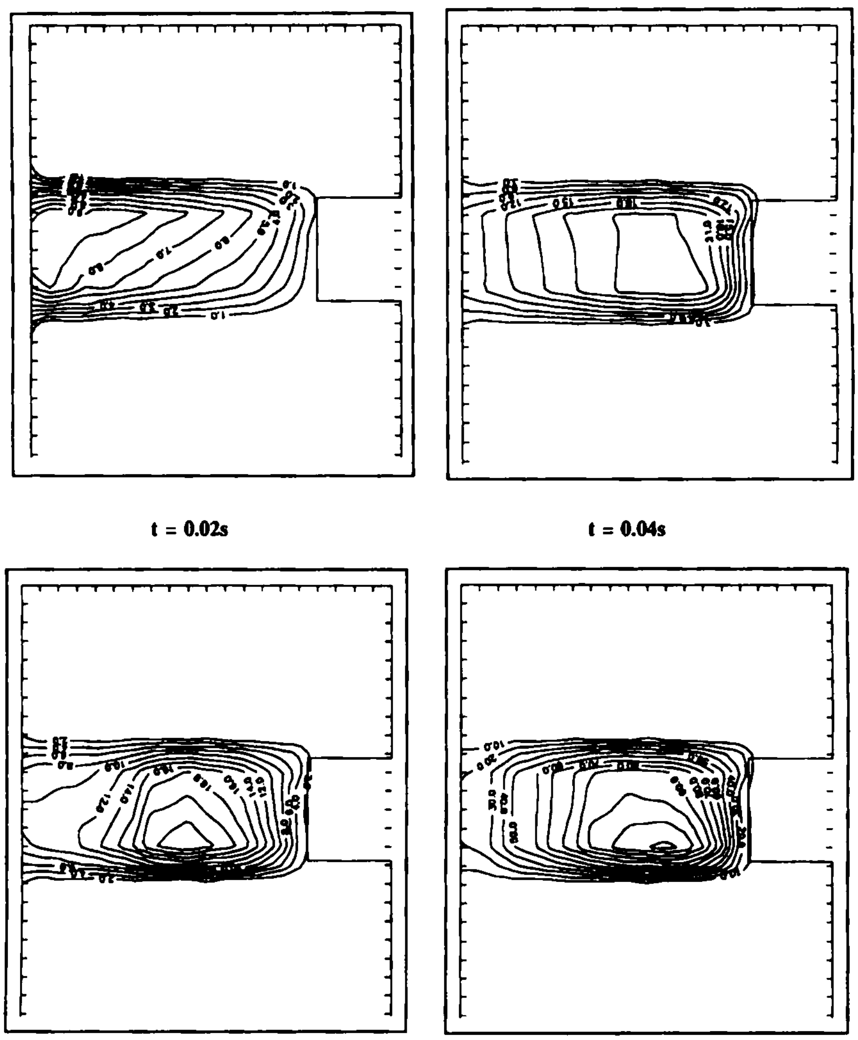
3. CONTINUITY OF METHANE GAS FLOW IN COAL SEAMS

The present study will involve two phases of methane gas transport. The first one is the transfer of free gas through the void space in the coal seam, and the second is the diffusion of adsorbed gas from the solid matrix of coal into the free phase within voids in the coal seam. Thus, the basic

approach should be regarded as the continuity of gas flow and conservation of transferred gas mass. In an elemental volume, the flow of methane gas mass per unit time can be described as in Table I.

Thus, the mass of methane gas flow in the elemental volume per unit time minus that of flow out and plus the diffused mass of desorbed methane gas within the elemental volume per unit time should be equal to the mass change rate of methane gas in this element

$$\frac{\partial(\rho_g \Phi)}{\partial t} + \frac{\partial}{\partial x_i}(\rho_g v_i \phi_i) = Q \tag{6}$$



t = 0.02s t = 0.04s

t = 0.06s t = 0.08s

Figure 5(a). Contours of gas concentration ($\times 10^{-4}$) in coal seam during outbursts

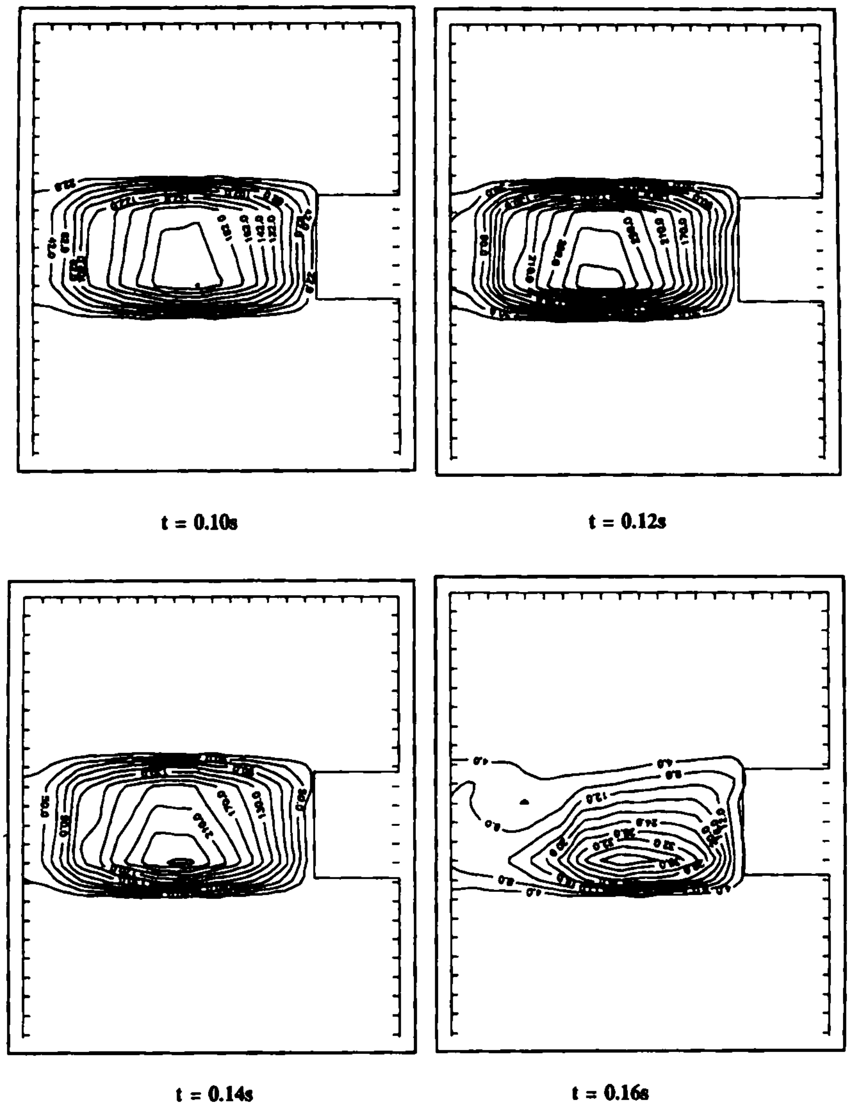


Figure 5(b). Contours of gas concentration ($\times 10^{-4}$) in coal seam during outbursts

where ρ_g is the mass density of methane gas under pressure P, v_i is the velocity of methane gas flow, and Q is the desorption rate of methane gas from adsorbed phase to free phase. The components of the specific discharge vector of gas flow in x_i direction can be expressed in terms of the corresponding components of gas flow velocity, v_i, and the reduction rate of area, ϕ_i, as

$$q_i = (v_i - v_{si})\phi_i \quad \text{(no summation for } i\text{)} \tag{7}$$

where v_{si} is the solid velocity along direction x_i

4. DIFFUSION OF ADSORBED METHANE GAS TO FREE PHASE

Diffusion of adsorbed methane gas is the process by which matter is transported from one part of the system to another part as a result of random molecular motion. This basic concept was recognized by Fick, who first quantified the diffusion equation by adopting the mathematical equation of mass conservation. According to Fick, the diffusion equation of adsorbed methane gas from the coal matrix to the void space in coal seam can be defined by

$$-\frac{\partial}{\partial x_i}\left(\rho G_i \frac{\partial C}{\partial x_i}\right) + \frac{\partial(\rho C)}{\partial t} = Q \tag{8}$$

where G_i is the coefficient of diffusion of methane gas from adsorbed phase to free phase. C is the concentration of methane gas in the coal seam under pressure P, which can be defined as the ratio

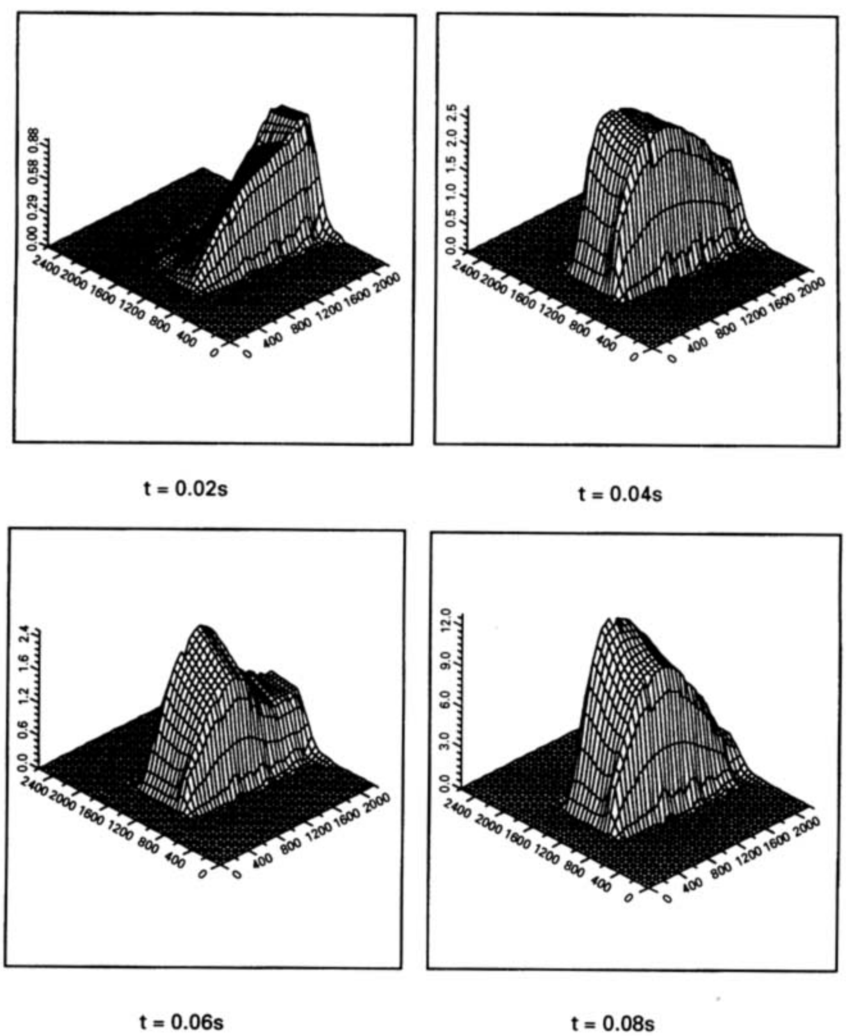


Figure 6(a). Pressure distribution of methane gas in coal seam during outbursts

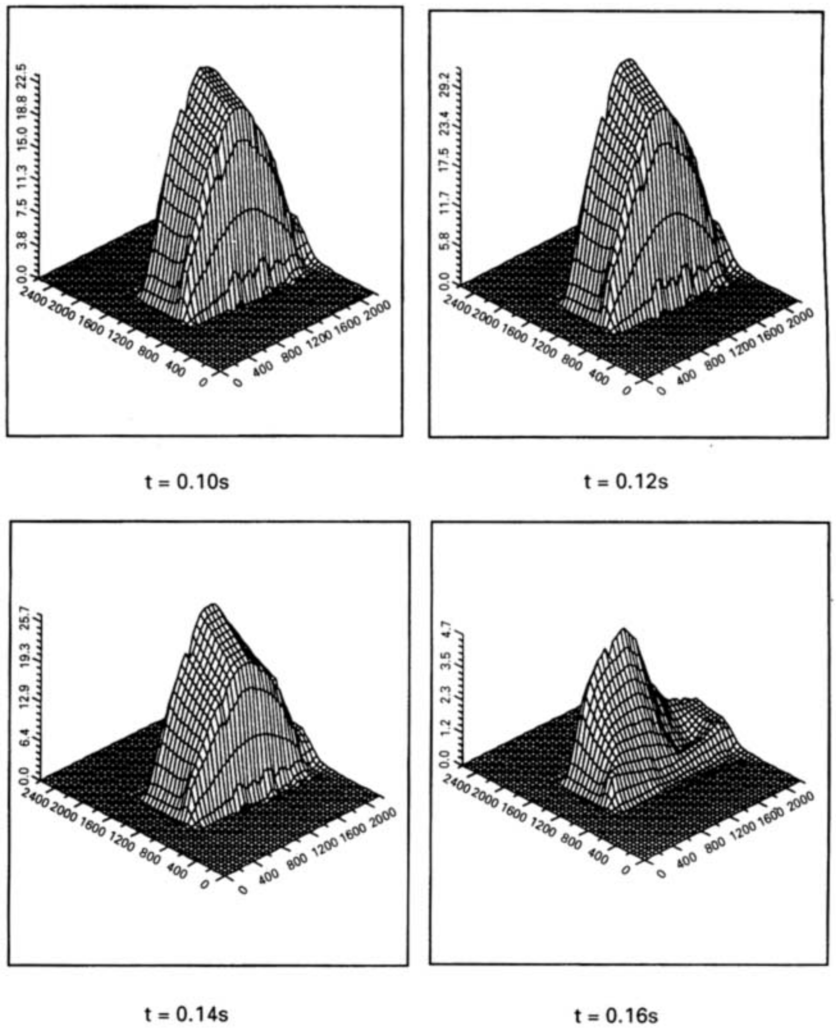


Figure 6(b). Pressure distribution of methane gas in coal seam during outbursts

of gas mass to the total mass per unit volume under pressure P. Q is the diffusion source which has been defined in equation (6). ρ is the mass density of the coal seam including methane gas in the unit volume of the coal seam. It can be found that there is an interesting relationship among the volumetric porosity, the mass density of methane gas and the mass density of the coal seam, (Φ, ρ_g and ρ_s).

$$\rho = \rho_s(1 - \Phi) + \rho_g\Phi \tag{9}$$

In this study, we will only consider the problem of porosity in steady-state case. Thus, we can assume that the porosity of coal seam does not change when the gas pressure varies and is constant within an element space. Therefore, we have, $\partial\Phi/\partial t = 0$ and $\partial\Phi/\partial x_i = 0$. The mass density of net coal seam without porosity, ρ_s can be assumed to be independent of time and space (i.e. $d\rho_s = 0$). Using the above assumptions and substituting equations (7) and (9) into equations

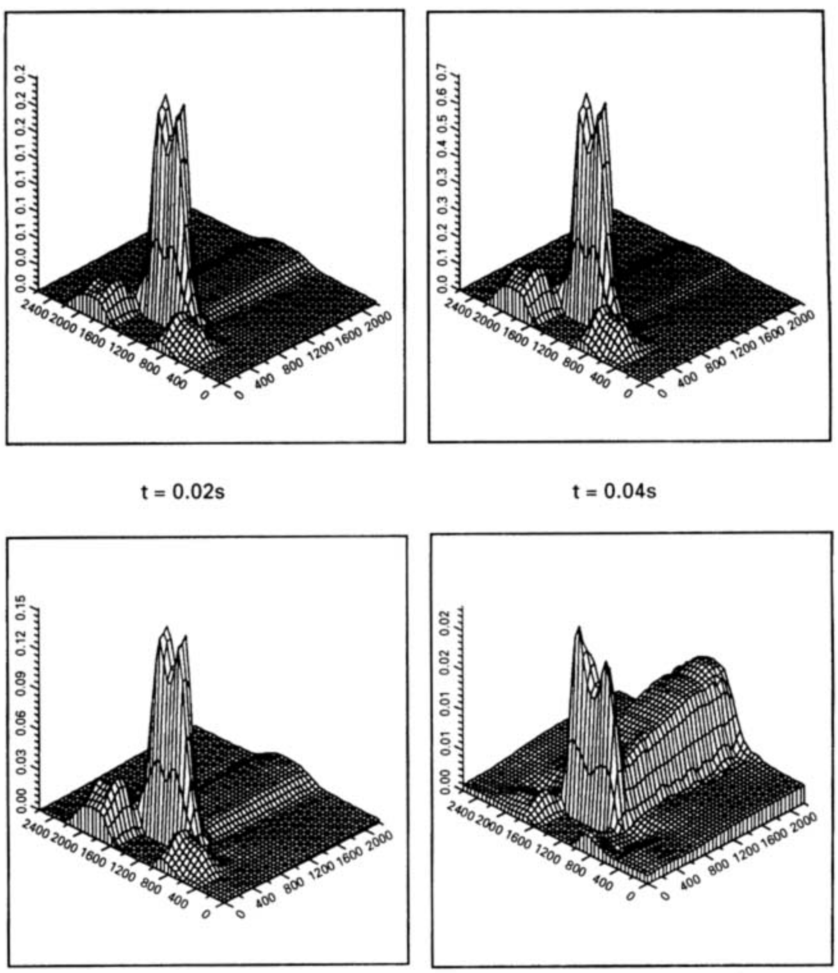
(6) and (8), we have

$$\Phi \frac{\partial \rho_g}{\partial t} - \rho_g \frac{\partial}{\partial x_i}\left(\frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\right) - \frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\frac{\partial \rho_g}{\partial x_i} + \phi_i \rho_g \frac{\partial v_{si}}{\partial x_i} + \phi_i v_{si}\frac{\partial \rho_g}{\partial x_i} = Q \tag{10}$$

$$\rho \frac{\partial C}{\partial t} + C\Phi \frac{\partial \rho_g}{\partial t} - \rho \frac{\partial}{\partial x_i}\left(G_i \frac{\partial C}{\partial x_i}\right) - \Phi \frac{\partial \rho_g}{\partial x_i} G_i \frac{\partial C}{\partial x_i} = Q \tag{11}$$

Substituting equation (11) into equation (10), we have

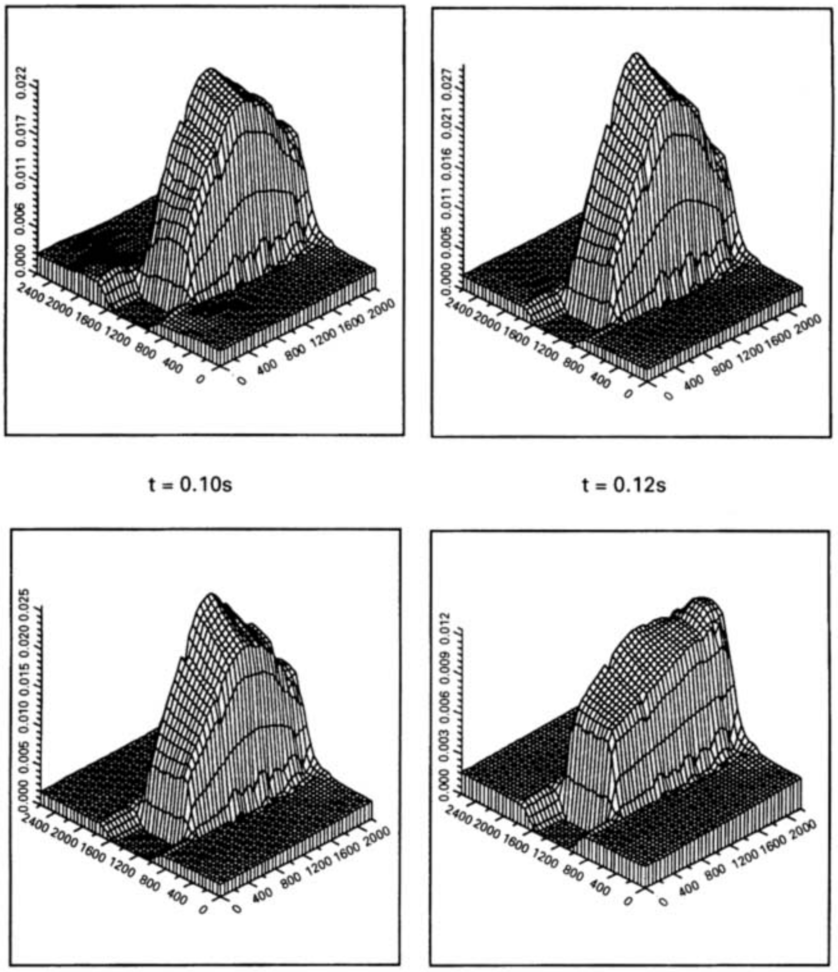
$$\phi_i \frac{\partial}{\partial t}\frac{\partial u_i}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\right) + \Phi \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial t} - \frac{k_i}{\mu}\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial x_i}\frac{\partial P}{\partial x_i} + \phi_i \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial x_i}\frac{\partial u_i}{\partial t} = Q^* \tag{12}$$



t = 0.02s t = 0.04s

t = 0.06s t = 0.08s

Figure 7(a). Distribution of strain energy per unit volume during outbursts



t = 0.10s t = 0.12s

t = 0.14s t = 0.16s

Figure 7(b). Distribution of strain energy per unit volume during outbursts

where

$$Q^* = \frac{\rho}{\rho_g}\frac{\partial C}{\partial t} - \frac{\rho}{\rho_g}\frac{\partial}{\partial x_i}\left(G_i\frac{\partial C}{\partial x_i}\right) + C\Phi\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial t} - \Phi\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial x_i}G_i\frac{\partial C}{\partial x_i} \tag{13}$$

5. RELATION BETWEEN PRESSURE AND CONCENTRATION OF GAS IN COAL SEAMS

In general, the mass density of gas varies with the pressure. Therefore, the measurement of concentration of gas should be under a given pressure, which is usually taken as atmospheric. Thus, the concentration of methane gas under pressure, P, in coal seam is defined as the ratio of

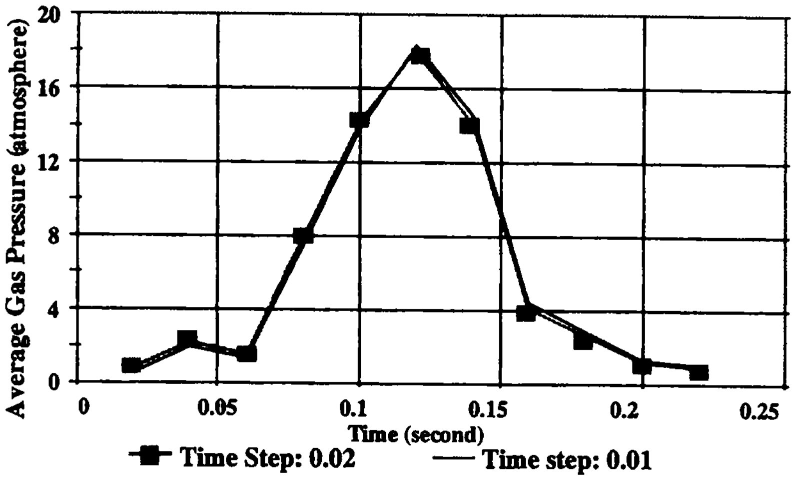


Figure 8(a). Average gas pressure in coal seam versus time during outbursts computed by different time steps in Newmark integration scheme

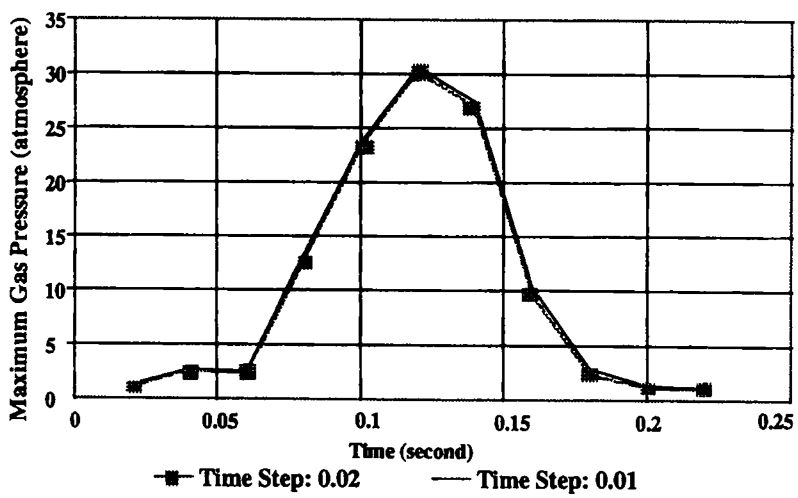


Figure 8(b). Maximum gas pressure in coal seam versus time during outbursts computed by different time steps in Newmark integration scheme

gas mass, m_g, to the total mass of net coal and gas, $m_s + m_g$, in a unit volume of coal seam.

$$C = \frac{m_g}{m_s + m_g} = \frac{\Phi \rho_g}{(1 - \Phi)\rho_s + \Phi \rho_g} = \frac{\rho_g}{\rho} \Phi \tag{14}$$

Equation (14) can be rewritten as

$$\rho_g = \frac{1 - \Phi}{\Phi} \frac{C}{1 - C} \rho_s \tag{15}$$

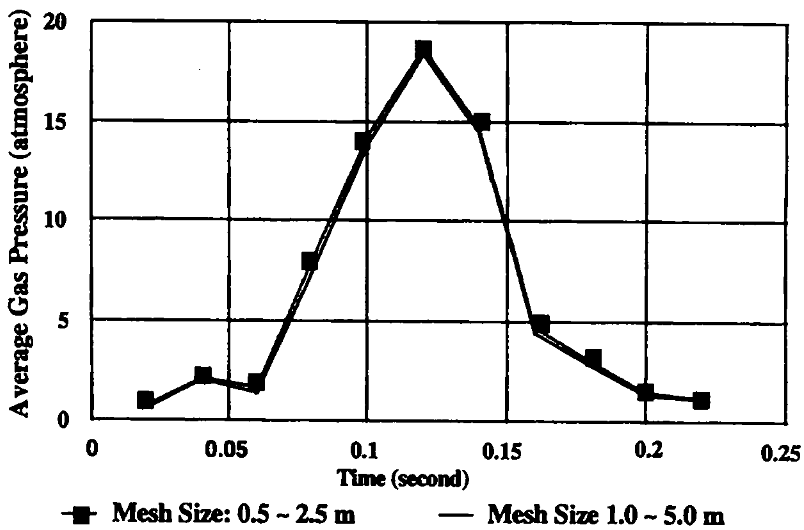


Figure 9(a). Average gas pressure in coal seam versus time during outbursts computed by different mesh size ($\Delta t = 0{\cdot}01$ s)

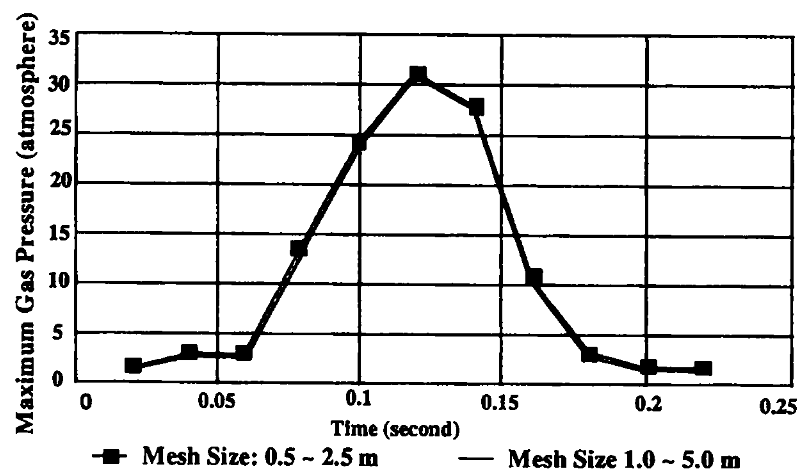


Figure 9(b). Maximum gas pressure in coal seam versus time during outbursts computed by different mesh size ($\Delta t = 0{\cdot}01$ s)

Equations (14) and (15) present a general relationship among the gas concentration, the mass densities of gas and coal and the porosity of the medium. It is possible to employ a general equation of gas state using compressibility factors. Based on the principles of thermodynamics, the isothermal compressibility for the gas is defined by

$$\alpha_p = \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P} \tag{16}$$

Equation (16) can be integrated to obtain ρ_g with the initial conditions, when $P = P_0$, $\rho_g = \rho_{g_0}$.

Then, we obtain

$$\rho_g = \rho_{g_0} \exp\left[\int_{P_0}^{P} \alpha_p \, dP\right] \tag{17}$$

Substituting equation (17) into equation (14), the relationship between methane gas concentration and gas pressure for a general gas model can be presented as

$$C = \frac{\Phi \rho_{g_0} \exp\left[\int_{P_0}^{P} \alpha_p \, dP\right]}{(1-\Phi)\rho + \Phi \rho_{g_0} \exp\left[\int_{P_0}^{P} \alpha_p \, dP\right]} \tag{18}$$

From equations (14)–(17), the following relationships between gas concentration and gas density under a given gas pressure can be written:

$$\frac{\partial \rho_g}{\partial C} = \frac{1-\Phi}{\Phi} \rho_s \frac{1}{(1-C)^2} \tag{19}$$

$$\alpha_c = \frac{1}{\rho_g} \frac{\partial \rho_g}{\partial C} = \frac{1}{C(1-C)} \tag{20}$$

$$\frac{\partial P}{\partial C} = \frac{1}{\alpha_P C(1-C)} \tag{21}$$

The relationships presented in equations (14)–(21) are general relationships which can be applied for any kind of gas model. In this paper, the above relationships for the ideal gas model will be applied under the isothermal condition for the problem of methane gas migration in coal seams. Based on the principles of thermodynamics, the ideal gas law is usually expressed in the form of $P_1 V_1 / T_1 = P_2 V_2 / T_2$, where subscripts 1 and 2 indicate two different gas states, V is the volume of the gas, and T is the absolute temperature. In the isothermal process, the volume of the gas under pressure P can be determined in terms of the volume of the gas under atmospheric pressure, P_0, such as $V = P_0 V_0 / P$. Thus, the mass density of methane gas under pressure P can be written in terms of the mass density of gas under atmospheric pressure (ρ_{g_0}), by using the equation, $\rho_g = P \rho_{g_0} / P_0$. Substituting this equation into equation (14), we have

$$C = \frac{\dfrac{\rho_{g_0}\Phi}{P_0} P}{(1-\Phi)\,\rho_s + \dfrac{\rho_{g_0}\Phi}{P_0} P} = \frac{bP}{a + bP} \tag{22}$$

where

$$a = (1-\Phi)\rho_s, \qquad b = \rho_{g_0}\Phi / P_0 \tag{23}$$

It can be noted that the relationship (equation (22)) is very similar to that of Langmuir's relation, $C = ABP/(1 + BP)$, where A and B are Langmuir's constants.[8] For the ideal gas model, equations (16), (17), (18) and (21) can be represented as follows:

$$\alpha_p = \frac{1}{P} \tag{24}$$

$$\rho_g = \frac{1-\Phi}{\Phi}\frac{C}{1-C}\rho_s = \frac{P}{P_0}\rho_{g_0} \tag{25}$$

$$P = \frac{1-\Phi}{\Phi}\frac{C}{1-C}\frac{\rho_s P_0}{\rho_{g_0}} = \frac{C}{1-C}\frac{a}{b} \tag{26}$$

$$\frac{\partial P}{\partial C} = \frac{P}{C(1-C)} = \frac{1}{(1-C)^2}\frac{a}{b} = \frac{1}{(1-C)^2}\frac{1-\Phi}{\Phi}\frac{\rho_s P_0}{\rho_{g_0}} \tag{27}$$

6. GOVERNING EQUATIONS OF METHANE GAS MIGRATION IN COAL SEAMS

From equations (15) and (17) it can be seen that the gas density is a function of pressure and concentration. Therefore, the partial differential of gas density with respect to time and space can be written as

$$\frac{\partial \rho_g}{\partial t} = \frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial t} + \frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial t} \tag{28}$$

$$\frac{\partial \rho_g}{\partial x_i} = \frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial x_i} + \frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial x_i} \tag{29}$$

The general governing equation of methane gas migration in coal seams can be derived from equations (12) and (13) by substituting the relationship of equation (14) and equations (28) and (29)

$$\phi_i \frac{\partial}{\partial t}\frac{\partial u_i}{\partial x_i} + \alpha_{p_0}\Phi\frac{\partial P}{\partial t} - \frac{\partial}{\partial x_i}\left(\frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\right) = Q_c^* \tag{30}$$

where α_{p_0} is the compressibility of methane gas under atmospheric pressure.

The term of Q_c^* in equation (30) can be rewritten as

$$Q_c^* = [\alpha_{p_0} + (C-1)\alpha_p]\Phi\frac{\partial P}{\partial t} + \alpha_P\frac{k_i}{\mu}\left(\frac{\partial P}{\partial x_i}\right)^2 - \alpha_c\Phi G_i\left(\frac{\partial C}{\partial x_i}\right)^2 - \frac{\Phi}{C}\frac{\partial}{\partial x_i}\left(G_i\frac{\partial C}{\partial x_i}\right)$$
$$+ \left(\alpha_c\frac{k_i}{\mu} - \alpha_p\Phi G_i\right)\frac{\partial P}{\partial x_i}\frac{\partial C}{\partial x_i} - \phi_i\frac{\partial u_i}{\partial t}\left(\alpha_p\frac{\partial P}{\partial x_i} + \alpha_c\frac{\partial C}{\partial x_i}\right) \tag{31}$$

where the terms, α_c and α_p, can be calculated for the ideal gas model from equations (20) and (24).

Equation (30) is the general governing equation of methane gas pressure during the gas migration in the coal seams. This is a non-linear partial differential equation with second order for space and first order for time. The non-linearity appears both in space and time domain. The concentration of methane gas in the coal seam can be calculated by equation (18) or equation (22) for the ideal gas model in terms of the gas pressure, P. It should be noted that the value of gas concentration obtained from equation (22) is the value exchanged from pressure, P, to atmospheric pressure. The value of gas concentration obtained from equation (18) is under pressure, P, with isothermal compressibility, α_p.

The interaction of the gas pressure and the deformation of the solid coal seam can be obtained from the general elastic dynamic equilibrium as follows:

The dynamic equilibrium equation of an elastic medium is

$$\frac{\partial \sigma_{ij}^*}{\partial X_j} + F_i = \rho_s\frac{\partial^2 u_i}{\partial t^2} \tag{32}$$

where σ^{*}_{ij} is the total stress in the medium, X_j ($i = 1, 2, 3$) indicates the tensor notation of the Cartesian co-ordinates (x, y, z). u_i is the displacement of solid and F_i is the body force per unit volume along X_i direction. The total stress can be expressed as

$$\sigma^{*}_{ij} = \sigma_{ij} + \sigma^{0}_{ij} - \chi\delta_{ij}P \tag{33}$$

where $(\sigma_{ij} - \chi\delta_{ij}P)$ is referred to as the 'effective' stress. σ^{0}_{ij} is the initial stress. χ is a physical constant, which is the ratio of the gas volume squeezed out to the volume change of the porous medium. If the latter is compressed while allowing the gas to escape, we have

$$\chi = 1 - \alpha_s/\beta \tag{34}$$

$$\beta = E/[3(1 - 2v)] \tag{35}$$

where α_s is the matrix compressibility of the coal seam, β is the bulk compressibility of the solid, E is the elastic modulus and v is the Poisson's ratio of the coal seam.

The stress–strain constitutive equation is

$$\sigma_{ij} = D_{ijlk}\varepsilon_{lk} \tag{36}$$

The strain–displacement equation is

$$\varepsilon_{lk} = \frac{1}{2}\left(\frac{\partial u_l}{\partial x_k} + \frac{\partial u_k}{\partial x_l}\right) \tag{37}$$

The equilibrium equation of the elastic medium with pore pressure can be represented in the Cartesian co-ordinates (x, y, z) as

$$\frac{1}{2}\frac{\partial}{\partial X_j}\left[D_{ijlk}\left(\frac{\partial u_l}{\partial X_k} + \frac{\partial u_k}{\partial X_l}\right)\right] - \chi\frac{\partial P}{\partial X_i} - \rho_s\frac{\partial^2 u_i}{\partial t^2} = -F_i - \frac{\partial \sigma^{0}_{ij}}{\partial X_j} \tag{38}$$

The gas equation should be transformed into the Cartesian co-ordinates (x, y, z), and the transformation gives

$$\phi_{*i}\frac{\partial}{\partial t}\frac{\partial u_i}{\partial X_i} + \alpha_{P_0}\Phi\frac{\partial P}{\partial t} - \frac{\partial}{\partial X_i}\left(\frac{k_{ij}}{\mu}\frac{\partial P}{\partial X_j}\right) = Q^{*}_{c} \tag{39}$$

where

$$Q^{*}_{c} = [\alpha_{p_0} + (C-1)\alpha_p]\,\Phi\frac{\partial P}{\partial t} + \alpha_P\frac{\partial P}{\partial X_i}\frac{k_{ij}}{\mu}\frac{\partial P}{\partial X_j} - \alpha_c\Phi\frac{\partial C}{\partial X_i}G_{ij}\frac{\partial C}{\partial X_j} - \frac{\Phi}{C}\frac{\partial}{\partial X_i}\left(G_{ij}\frac{\partial C}{\partial X_j}\right)$$
$$+ \frac{\partial P}{\partial X_i}\left(\alpha_c\frac{k_{ij}}{\mu} - \alpha_p\Phi G_{ij}\right)\frac{\partial C}{\partial X_j} - \frac{\partial u_i}{\partial t}\phi_{ij}\left(\alpha_p\frac{\partial P}{\partial X_j} + \alpha_c\frac{\partial C}{\partial X_j}\right) \tag{40}$$

in which the permeability tensor, k_{ij}, and the diffusibility tensor, G_{ij}, of the anisotropic porous medium can be determined from the principal values by co-ordinate transformation as

$$k_{ij} = T_{il}k_l\delta_{lk}T_{kj}, \quad G_{ij} = T_{il}G_l\delta_{lk}T_{kj} \tag{41}$$

$$\phi_{ij} = T_{il}\phi_l\delta_{lk}T_{kj}, \quad \phi_{*i} = T_{ij}\phi_j \tag{42}$$

where T_{ij} is the co-ordinate transformation tensor.

7. FINITE ELEMENT MODELLING OF METHANE GAS MIGRATION IN COAL SEAMS

Equations (38)–(40) form the required system of coupled non-linear partial differential equations. We now consider a two-dimensional plane strain situation. For convenience, we assume that the material parameters, k_{ij}, G_{ij}, D_{ijkl}, ϕ_i, Φ, α_P, α_c, β, ρ, χ, ρ_{g_0} are constants within an element. The general finite element discretization procedure for equations (38)–(40) can be obtained using the standard Galerkin's method. However, this procedure presents a difficulty because of the non-linear system of equations. Therefore, an iterative method has been introduced in the finite element discretization.

It should be noted that when applying Galerkin's procedure to equations (38) and (40), Q_c^* is the function of gas concentration, and can be written in the form of $Q_c^* = Q_c^*(C, x, y, t)$. Thus, the finite element formulation for equations (38)–(40) can be written as

$$\begin{bmatrix} [K_{ij}] & [A_{ij}] \\ [0] & [S_{ij}] \end{bmatrix} \begin{Bmatrix} \{U\} \\ \{P\} \end{Bmatrix} + \begin{bmatrix} [0] & [0] \\ [N_{ij}] & [H_{ij}] \end{bmatrix} \begin{Bmatrix} \{\dot{U}\} \\ \{\dot{P}\} \end{Bmatrix} + \begin{bmatrix} [M_{ij}] & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{U}\} \\ \{\ddot{P}\} \end{Bmatrix} = \begin{Bmatrix} \{\bar{F}^*\} \\ \{\bar{Q}^*\} \end{Bmatrix} \tag{43}$$

In the static case, the solid acceleration term in equation (43) can be neglected. Thus, on application of a general weighted finite difference time-stepping scheme, equation (43) becomes

$$\begin{bmatrix} [K_{ij}] & [A_{ij}] \\ [N_{ij}] & [S_{ij}^*] \end{bmatrix} \begin{Bmatrix} \{U\} \\ \{P\} \end{Bmatrix}_{n+1} = \begin{Bmatrix} \{\bar{F}^*\} \\ \{\bar{Q}^*\}_n + \{\bar{R}^*\}_n \end{Bmatrix} \tag{44}$$

where

$$[K_{ij}] = \int_{R^e} [B]^{\mathrm{T}}[D]\,[B]\,\mathrm{d}R \tag{45}$$

$$[N_{ij}] = \int_{R^e} \left[\frac{\partial \psi_i}{\partial X_k} \psi_j \phi_{*k}\right] dR, \quad [H_{ij}] = \int_{R^e} \alpha_{P_0} \Phi [\psi_i \;\; \psi_j]\,\mathrm{d}R \tag{46}$$

$$[A_{ij}] = -\int_{R^e} \left[\frac{\partial \psi_i}{\partial x} \;\; \frac{\partial \psi_i}{\partial y}\right]^{\mathrm{T}} \psi_j \chi\, dR \tag{47}$$

$$[S_{ij}^*] = \int_{R^e} \left[\theta\,\Delta t \frac{k_{kl}}{\mu} \frac{\partial \psi_i}{\partial X_k} \frac{\partial \psi_j}{\partial X_l} + \alpha_{P_0} \Phi \psi_i \;\; \psi_j\right] \mathrm{d}R \tag{48}$$

$$\bar{Q}_i^* = \int_{R^e} \psi_i\,\Delta t\, Q_c^*(C, x, y, t)\,\mathrm{d}R \tag{49}$$

$$\{\bar{F}_i^*\} = \int_{B_1^e} \psi_i \{S\}\,\mathrm{d}B_1 + \int_{R^e} \psi_i \{F\}\,\mathrm{d}R - \int_{R^e} \left[\frac{\partial \psi_i}{\partial x} \;\; \frac{\partial \psi_i}{\partial y}\right]^{\mathrm{T}} [\sigma^0]\,\mathrm{d}R \tag{50}$$

in which ψ_i is the shape function, $S_i = \tau_{ij} n_j$ is the surface traction boundary condition on B_1^e

$$\bar{R}_i^* = \int_{R^e} \left(\alpha_{P_0} \Phi \psi_k \psi_l - (1-\theta)\,\Delta t \frac{k_{ij}}{\mu} \frac{\partial \psi_k}{\partial X_i} \frac{\partial \psi_l}{\partial X_j}\right) P_k^{(n)}\,\mathrm{d}R + \int_{R^e} \frac{\partial \psi_i}{\partial X_k} \psi_j \phi_{*k} U_{kj}^{(n)}\,\mathrm{d}R + \int_{B_2^e} \psi_i\,\Delta t\, q^*\,\mathrm{d}B_2 \tag{51}$$

where q^* is the outward gas flux normal to the boundary surface B_2^e.

$$q^* = -\frac{k_{ij}}{\mu}\frac{\partial P}{\partial X_i}n_j \tag{52}$$

in which n_j is the outward normal vector.

The integration of equation (49) can be carried out using a Gaussian scheme through the values of Q_c^* and ψ_i at Gaussian points as

$$Q_k^* = \sum_i \sum_j W(\xi_i, \eta_j)\psi_k(\xi_i, \eta_j)\Delta t\, Q_c^*(C(\xi_i, \eta_j, t), \xi_i, \eta_j, t) \tag{53}$$

in which $W(\xi_i, \eta_j)$ is the weighting function of Gaussian interpolation scheme, Q_c^* is calculated from equation (40) by substituting the values, C, grad C, P, grad P, $\partial C/\partial t$, $\partial P/\partial t$, U, $\partial U/\partial t$ at the Gaussian points obtained by solving equations (43) or (44) at the time.

8. COMPUTATIONAL PROCEDURE

The iterative steps to solve this problem are as follows:

(1) Start from time $t = t_0$, to calculate the initial values of $(Q_k^*)_0$, from the given initial values of C, grad C, P, grad P, $\partial C/\partial t$, $\partial P/\partial t$, U, $\partial U/\partial t$ at the Gaussian points.
(2) Substitute the initial values of (Q_k^*) for all Gaussian points into equations (49) and (44) to solve the new values of C, grad C, P, grad P, $\partial C/\partial t$, $\partial P/\partial t$, U, $\partial U/\partial t$ at time $t = t_0$ for all nodal points.
(3) Calculate the values of C, grad C, P, grad P, $\partial C/\partial t$, $\partial P/\partial t$, U, $\partial U/\partial t$ at the Gaussian points in terms of Gaussian interpolation scheme.
(4) Substitute the values of C, grad C, P, grad P, $\partial C/\partial t$, $\partial P/\partial t$, U, $\partial U/\partial t$ at the Gaussian points into equation (52) to calculate the new value of $(Q_k^*)_{(m)}$ for the first time step $t = t_0$.
(5) Repeat steps (2)–(4) until convergence conditions $\| U_{(m+1)} - U_{(m)} \| < \varepsilon$ and $\| P_{(m+1)} - P_{(m)} \| < \varepsilon$ are satisfied.
(6) Go the next time step $t^{(n)}$ and repeat steps (2)–(5).

9. NUMERICAL RESULTS

The gas migration in coal seams is a complicated process because it involves two distinctly different flow processes. (i) diffusion of adsorbed methane from the interior of the coal matrices, or micro-pores to nearby cleats or fractures or macro-pores; (ii) free (gas and water) flow through the macro-pores to the working face. This transport process of the methane gas in coal seams is illustrated by Figure 3.

The geometry of an underground mine and the finite element mesh are shown in Figure 4. The depth from the surface to the top of the analysed region is assumed as 132 m. The analysed region is 26 m along vertical direction and 22 m along horizontal direction. The coal seam with 17 m length and 6 m depth is horizontally layered between two rock layers of 10 m wide.

In practice, the gas outbursts occur within a short period after a rock/coal burst. In order to simulate the process of methane gas migration during gas outbursts, it is assumed that a dynamic loading acts at the coal seam near the boundary of the working face during the burst. The dynamic load for the analysis is assumed as: peak tension (98·1 MPa); rise time (0–0·04 s); decay time (to 0·12 s). The total period in this analysis is considered to be 0·24 s.

The necessary material constants of methane gas in this analysis are taken as follows: mass density of gas at atmospheric pressure, $\rho_{g_0} = 0{\cdot}125 \times 10^{-4}$ (kg/cm^3);[9] compressibility of methane gas, $\alpha_{p_0} = 9{\cdot}81$ (1/M Pa); atmospheric pressure, $P_0 = 0{\cdot}1013$ (MPa). The material properties for the solid medium considered in this example are given in Table II.

For the solid medium, the displacement along the y direction on the top and bottom boundaries and along the x direction on the left and right boundaries of the analysed region were fixed. The initial displacement and velocity of the solid medium were assumed to be zero within the region. The boundary and initial conditions for the gas medium are considered only within the coal seam region. In order to simplify the analysis, the initial gas pressure within the coal seam is assumed to be unit atmospheric pressure. The value of the methane gas pressure at the coal seam boundary far from the working face is assumed to be the same as the initial value.

Figure 5 shows the distribution of gas concentration in the coal seam during outbursts in the form of contours. The maximum concentration (0·03) of methane gas within the coal seam exists at time $t = 0{\cdot}12$ s while the loading already decays to zero. Figure 6 illustrates the distribution of methane gas pressure during gas outbursts. From this set of figures, it can be noted that the gas outbursts in coal seams may happen in the period from $t = 0{\cdot}1$ s to $t = 0{\cdot}14$ s after the burst, because of the significantly decreasing gas pressure after $t = 0{\cdot}14$ s, as shown in Figure 6. The highest gas pressure appears to be in the middle of the coal seam and near the bottom of the coal seam layer. The gradient of the gas pressure along the vertical direction indicates that the gas flow is from the bottom to the top within the coal seam, and the highest gradient of the gas pressure along the vertical direction appears to be at the middle of the coal seam inside. The gradient of the gas pressure along the horizontal direction indicates that the gas flows from the middle area towards the ends, one towards the working face and the other towards the inside of the coal seam. Figure 7 shows the distribution of strain energy per unit volume during outbursts. It should be pointed that during the period before 0·08 s, the distribution of strain energy is similar to the stress distribution, and after a time of 0·08 s, it is controlled by the gradient of the gas pressure caused by methane gas release from adsorbed phase to free gas phase as shown in Figure 6. Thus, it can be stated that the form of strain energy distribution in the coal seam gives an indication of the possible occurrence of gas outbursts.

In order to investigate the accuracy of the finite element results, two different mesh divisions and two different time steps for numerical integration were adopted. The results for these analyses are shown in Figure 8 and 9. As can be seen, the difference in results between the different sets is quite negligible.

From the results presented in this study, the process of gas outbursts in coal seams can be described as follows:

During the first state of outbursts, the rock mass and the coal seam near the working face are fractured by the tensile stress. The gas pressure is then released within the coal seam, and a distribution of gas pressure from the inside of the coal seam towards the working face appears in the coal layer. During the second stage of outbursts, the tension zone propagates towards the inside of the coal seam and causes an increase of micro-cracks in the coal seam. This process affects the methane gas to start diffusion from the adsorbed phase in the coal matrix to the gas phase in the micro-pores, and causes the pressure of methane gas to increase within the entire coal seam region. Because of the presence of open macro-cracks (macro-pores), the pressure of the methane gas in the coal seam could not reach the highest pressure at this period. During the decay time, the macro-cracks in the coal seam may close, but the micro-cracks are still open and the diffusion of methane gas from adsorbed phase in the coal matrix to the gas phase in the micro-pores becomes faster, and the peak distribution appears. At time $t = 0{\cdot}12$ s, the tensile stress decays to zero, and the macro-cracks close, but the desorption of methane gas reaches the

fastest diffusion stage. The methane gas pressure in the coal seam increases significantly. As soon as the gas ejection starts, the pressure is released, and the gas concentration decreases. This phenomenon can be observed from the plots shown in Figures 5 and 6.

10. CONCLUSIONS

A mathematical model for the simulation of methane gas migration in coal seams is presented. This model is based on the coupled relationship among gas pressure, mass transfer, deformation and porosity of coal. In order to include all these aspects, a non-linear partial differential equation has been developed. This has been transformed into finite element equations using Galerkin's method and an iterative technique. Numerical results are presented for a coal mining problem. Through these results, the process of gas outbursts in coal seams has been explained.

APPENDIX I: DERIVATION OF EQUATIONS (30) AND (31):

Substituting equations (28) and (29) into equations (13) and (14), we have

$$\phi_i \frac{\partial}{\partial t}\frac{\partial u_i}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\right) + \Phi\left(\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial t} + \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial t}\right) \tag{54}$$

$$- \frac{k_i}{\mu}\left(\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial x_i} + \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial x_i}\right)\frac{\partial P}{\partial x_i} + \phi_i\left(\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial x_i} + \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial x_i}\right)\frac{\partial u_i}{\partial t} = Q^*$$

$$Q^* = \frac{\rho}{\rho_g}\frac{\partial C}{\partial t} - \frac{\rho}{\rho_g}\frac{\partial}{\partial x_i}\left(G_i\frac{\partial C}{\partial x_i}\right) + C\Phi\left(\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial t} + \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial t}\right) \tag{55}$$

$$- \Phi\left(\frac{1}{\rho_g}\frac{\partial \rho_g}{\partial P}\frac{\partial P}{\partial x_i} + \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial C}\frac{\partial C}{\partial x_i}\right)G_i\frac{\partial C}{\partial x_i}$$

Introducing the coefficients of isothermal compressibility for methane gas, α_p and α_c defined in equations (16) and (20), into equations (54) and (55), the equation can be rewritten in the simple form as

$$\begin{aligned}\phi_i \frac{\partial}{\partial t}\frac{\partial u_i}{\partial x_i} + \alpha_{P_0}\Phi\frac{\partial P}{\partial t} - \frac{\partial}{\partial x_i}\left(\frac{k_i}{\mu}\frac{\partial P}{\partial x_i}\right) &= [\alpha_{P_0} + (C-1)\alpha_P]\Phi\frac{\partial P}{\partial t} + \frac{\Phi}{C}\frac{\partial C}{\partial t} - \Phi\alpha_c(1-C)\frac{\partial C}{\partial t} \\ &\quad + \alpha_p\frac{k_i}{\mu}\left(\frac{\partial P}{\partial x_i}\right)^2 - \alpha_c\Phi G_i\left(\frac{\partial C}{\partial x_i}\right)^2 - \frac{\Phi}{C}\frac{\partial}{\partial x_i}\left(G_i\frac{\partial C}{\partial x_i}\right) \\ &\quad + \left(\alpha_c\frac{k_i}{\mu} - \alpha_p\Phi G_i\right)\frac{\partial P}{\partial x_i}\frac{\partial C}{\partial x_i} - \phi_i\frac{\partial u_i}{\partial t}\left(\alpha_p\frac{\partial P}{\partial x_i} + \alpha_c\frac{\partial C}{\partial x_i}\right)\end{aligned} \tag{56}$$

When substituting relationship, $\alpha_c(1-C) = 1/C$ (see equation (20)), it has

$$\frac{\Phi}{C}\frac{\partial C}{\partial t} - \Phi\alpha_c(1-C)\frac{\partial C}{\partial t} = 0$$

then equations (30) and (31) can be obtained.

APPENDIX II: DERIVATION OF EQUATION (44)

In order to integrate equation (43) in the static case, we introduce a θ family approximation which approximates a weighted average of time derivative of a dependent variable at two consecutive time steps by a linear interpolation of the values of the variable at two time steps

$$\theta\{\dot{U}\}_{n+1} + (1-\theta)\{\dot{U}\}_n = \frac{1}{\Delta t}(\{U\}_{n+1} - \{U\}_n) \tag{57}$$

$$\theta\{\dot{P}\}_{n+1} + (1-\theta)\{\dot{P}\}_n = \frac{1}{\Delta t}(\{P\}_{n+1} - \{P\}_n) \tag{58}$$

In static case, the solid acceleration term in equation (43) can be neglected, and at time step (n) and ($n+1$), equation (43) can be represented as

$$\theta[K]\{U\}_{n+1} + \theta[A]\{P\}_{n+1} = \theta\{\bar{F}^*\} \tag{59}$$

$$\theta[S]\{P\}_{n+1} + \theta[N]\{\dot{U}\}_{n+1} + \theta[A]\{\dot{P}\}_{n+1} = \theta\{\bar{Q}^*\}_{n+1} \tag{60}$$

$$(1-\theta)[S]\{P\}_n + (1-\theta)[N]\{\dot{U}\}_n + (1-\theta)[A]\{\dot{P}\}_n = (1-\theta)\{\bar{Q}^*\}_n \tag{61}$$

Substituting equations (57) and (58) into equation (60) and (61), we have

$$\begin{aligned}[N]\{U\}_{n+1} + ([H] + \theta\,\Delta t[S])\{P\}_{n+1} = \theta\,\Delta t\{\bar{Q}^*\}_{n+1} + (1-\theta)\Delta t\{\bar{Q}^*\}_n + [N]\{U\}_n \\ + ([H] + \theta\,\Delta t[S])\{P\}_n\end{aligned} \tag{62}$$

in which

$$\theta\,\Delta t\{\bar{Q}^*\}_{n+1} + (1-\theta)\Delta t\{\bar{Q}^*\}_n = \Delta t\{\bar{Q}^*\}_n + \Delta t^2\left\{\frac{\partial\bar{Q}^*}{\partial t}\right\}_n$$

Neglecting the term with second order to time, equation (62) can be rewritten as

$$[N]\{U\}_{n+1} + [S^*]\{P\}_{n+1} = \Delta t\{\bar{Q}^*\}_n + [N]\{U\}_n + ([H] - (1-\theta)\,\Delta t[S])\{P^*\}_n \tag{63}$$

where

$$[S^*_{ij}] = [H_{ij}] + \theta\,\Delta t[S_{ij}]$$

Equation (44) can be obtained by rewriting equation (59) together with equation (63) in matrix form.

APPENDIX III: DESCRIPTION OF MESH SIZE AND TIME STEP ALGORITHM

In this analysis, the dynamic load is shown in Figure 10. From the figure, it can be seen that the period is

$$\frac{T}{2} = 0{\cdot}12 \text{ (s)} \quad \text{and} \quad T = 0{\cdot}214 \text{ (s)}$$

The frequency of the dynamic load period is

$$f = \frac{1}{T} = 4{\cdot}1667 \text{ (Hz)}$$

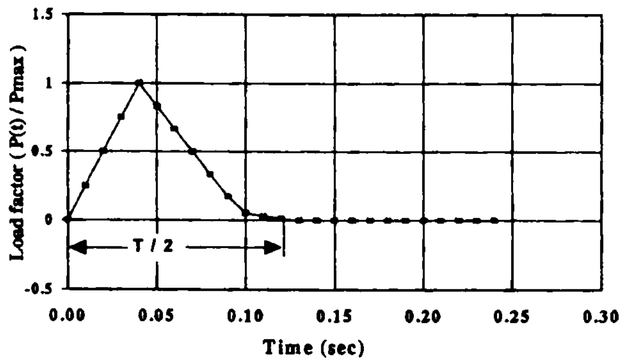


Figure 10.

From Table (II), the shear modulus of coal can be calculated as

$$G = \frac{E}{2(1+\nu)} = 2{\cdot}796 \times 10^4 \ \text{(MPa)} = 2{\cdot}743 \times 10^5 \ (\text{kg cm/s}^2)$$

The shear wave speed in the coal seam can be determined as

$$v_s = \sqrt{\frac{G}{\rho_s}} = \sqrt{\frac{2{\cdot}769 \times 10^5}{0{\cdot}853 \times 10^{-3}}} = 1{\cdot}8368 \times 10^4 \ \text{(cm/s)}$$

The shear wave length is

$$\lambda = \frac{v_s}{f} = \frac{1{\cdot}8368 \times 10^4}{4{\cdot}2} = 4{\cdot}3733 \times 10^3 \ \text{(cm)}$$

The generally proposed mesh dimension for this type of problems vary from $\lambda/10$ to $\lambda/6$.[14] In this case, it is say, 430 to 700 cm. Whereas the maximum and minimum mesh sizes used here are

$$\text{d min} = 100 \ \text{(cm)}$$

$$\text{d max} = 500 \ \text{(cm)}$$

The time step for Newmark integration scheme is

$$\Delta t = 0{\cdot}01 \ \text{(s)}$$

which is less than $T/10$.

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